Patent Application of

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for

Multiple Channel Optical Frequency Mixers for All-Optical Signal Processing

RELATED APPLICATIONS

This application claims priority from Provisional Patent Application 60/206,874 filed on 5/24/2000 and from Provisional Patent Application entitled "Multiple Channel Optical Frequency Mixers for All-Optical Signal Processing" filed on 2/1/2001, both of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to multi-channel optical frequency mixers using quasi-phase-matching for all-optical signal processing, and in particular to quasi-phase-matching gratings engineered to have multiple quasi-phase-matched channels for performing frequency mixing operations.

BACKGROUND OF THE INVENTION

The drive for robust, high-capacity information networks has resulted in many advances in the field of optical signal routing and processing. While most local networks still rely on

electronics, many long distance communications lines are using optical signals to transmit information. Depending on the transmission protocols selected and transmission characteristics of the optical components used, the information-bearing optical signals are contained in a number of channels at predetermined optical frequencies. There are numerous protocols for defining channel parameters, including Wavelength Division Multiplexing (WDM) or Dense Wavelength Division Multiplexing (DWDM) protocols. The waveguides used in these long distance networks are optical fibers, which offer advantages such as low loss, immunity to interference and, most importantly, an extremely large bandwidth.

To transmit information, data is modulated on optical carrier signals of wavelengths corresponding to the selected channels (e.g., WDM channels). The information-bearing carrier signals are combined at the transmitting end and sent via the optical fiber to the receiving end. Along the way, the signals encounter various active and passive network elements including routing nodes, frequently equipped with repeaters and dispersion compensation elements among others. Traditionally, at many of these nodes the signals are converted back into electronic form for processing. Afterwards, they are converted back into optical signals as they leave the node. Speed, bandwidth and power requirements can be limiting due to this conversion.

The above problems are circumvented in an all-optical network in which the nodes switch optical signals in the different wavelength channels in different directions generally without

converting the optical signals into electronic form. Several concepts for all-optical WDM networks have been developed for this purpose. The fundamentals of all-optical routing operations require the ability to discriminate between two signals of wavelengths λ_1 and λ_2 and to switch them to different optical paths based on their wavelengths. Switches which can perform such operations are known in the art and include, among other, acousto-optically or electro-optically tunable filters and micro-electromechanical systems (MEMS). In addition, all-optical switches should also be able to perform wavelength conversion functions, i.e., switch the two optical signals between different optical carrier wavelengths, either within the immediate network or when transferring to a neighboring network. Such wavelength switches can be used to build wavelength interchangers or wavelength interchanging cross-connects. More information about such switches is provided by S.J.B. Yoo in "Wavelength Conversion Technologies for WDM Network Applications", Journal of Lightwave Technology, Vol. 14, No. 6, June 1996, pp. 955-66 as well as in U.S. Pat. No. 5,825,517 to Antoniades et al. and in the references cited therein.

In a practical all-optical network the nodes have to be able to perform frequency mixing operations on a large number of optical signals of different wavelengths, i.e., multiple signals contained in different channels. One way to achieve frequency mixing operations on a number of signals at multiple wavelengths is to employ separate discrete single channel devices. Typically, single channel frequency mixing devices employ an optical material exhibiting a nonlinear susceptibility to

perform one or more frequency mixing operations. Among other, such operations can include second harmonic generation (SHG), difference frequency generation (DFG), sum frequency generation (SFG), or parametric amplification. For example, it is sometimes useful to perform SHG followed by DFG, which uses the second harmonic generated by SHG. General information about wavelength conversion in multiple WDM channels is provided by Lacey, J.P.R. et al., in "Four-Channel Polarization-Insensitive Optically Transparent Wavelength Converter", IEEE Photonics Technology Letters, Vol. 9, No. 10, Oct. 1997, pp. 1355-7.

To achieve efficient frequency conversion many devices use quasi-phase-matching (QPM) to counteract the phase slip between the generating nonlinear polarization and the generated or converted optical field as these propagate through the nonlinear optical material. Thus, there is a phase velocity mismatch between the generating polarization and generated optical signals. QPM employs a grating in the nonlinear material to periodically compensate for this phase velocity mismatch. There are several methods for producing and tuning such QPM gratings and general information on the theory and applications of QPM within optical waveguides can be found in Michael L. Bortz's Doctoral Dissertation entitled "Quasi-Phasematched Optical Frequency Conversion in Lithium Niobate Waveguides", Stanford University, 1995 as well as M.L. Bortz et al., "Increased Acceptance Bandwidth for Quasiphasematched Second Harmonic Generation in $LiNbO_3$ Waveguides", Electronics Letters, Vol. 30, 1/6/1994, pp. 34-5.

Several prior art references teach the use of QPM for purposes of phasematching signals with do not bear information. For example, U.S. Pat. Nos.: 5,644,584 to Nam et al.; 5,912,910 to Sanders et al.; 6,021,141 to Nam et al. and Becouarn, L. et al., "Cascaded Second-Harmonic and Sum-Frequency Generation of a CO_2 Laser Using a Single Quasi-Phase-Matched GaAs Crystal", Conference on Lasers and Electro-Optics, IEEE, Vol. 6, pp. 146-7, 1998 teach conversion of output signals from lasers and conversion of optical signals which do not carry information.

Meanwhile, specific application of QPM based wavelength converters dealing with information-bearing signals and including WDM applications are discussed by C.Q. Xu et al., "1.5 μm Band Efficient Broadband Wavelength Conversion by Difference Frequency Generation in a Periodically Domain-Inverted $LiNbO_3$ Channel Waveguide", Applied Physics Letters, Vol. 63, 27 December 1993, pp. 3559-61; C.Q. Xu et al., "Efficient Broadband Wavelength Converter for WDM Optical Communication Systems", Conference on Optical Fiber Communication, IEEE, 20-25 Feb. 1994; M.H. Chou et al., "1.5-μm-Band Wavelength Conversion Based on Cascaded Second-Order Nonlinearity in $LiNbO_3$ Waveguides", IEEE Photonics Technology Letters, Vol. 11, No. 6, June 1999, pp. 653-5; as well as M.H. Chou et al., "1.5-μm-Band Wavelength Conversion Based on Difference-Frequency Generation in $LiNbO_3$ Waveguides with Integrated Coupling Structures", Optics Letters, Vol. 23, No. 13, July 1 1998, pp. 1004-6. In addition, U.S. Pat. No. 5,434,700 to Yoo teaches an all-optical wavelength converter which uses an optical waveguide with regions having differing nonlinear optical susceptibilities such that the

regions form a quasi-phase-matching grating. This single channel device is proposed for use in optical WDM networks to convert a single signal frequency.

Further, U.S. Pat. No. 5,815,307 to M. Arbore et al., and U.S. Pat. No. 5,867,304 to Galvanauskas et al. teach the use of aperiodic QPM gratings. In particular, these references teach the use of aperiodic QPM gratings in nonlinear materials for simultaneous frequency conversion and compression of optical pulses.

Unfortunately, setting up a number of single channel devices to perform frequency mixing operations on a number of signals in parallel is usually impractical and introduces excessive losses in the network. This is especially true when the number of channels or wavelengths is large, e.g., in the case of DWDM. Hence, it would be a significant advance to provide an apparatus and method for performing frequency mixing operations on signals in many wavelength channels simultaneously without having to use a number of dedicated single channel devices. Specifically, it would be very useful to have such apparatus tuned for frequency mixing operations using more than one short wavelength signals by having corresponding short wavelength channels.

OBJECTS AND ADVANTAGES

In view of the above, it is a primary object of the present invention to provide a multi-channel optical frequency mixer for frequency mixing operations. In particular, the frequency mixer

is to be quasi-phase-matched to at least two short wavelength channels for performing these mixing operations.

It is also an object of the invention to provide a method for defining a quasi-phase-matching grating to achieve quasi-phase-matching in a number of short wavelength channels.

Yet another object of the invention is to provide a multi-channel optical frequency mixer and methods for engineering such mixers for phasematching wavelengths whose location and spacing is defined by the International Telecommunication Union (ITU) standards.

It is an additional object of the invention to provide a multi-channel optical frequency mixer which can be employed in devices such as a multiple channel add/drop, a multiple channel switch and a multiple channel optical sampler. The multi-channel mixer of the invention should likewise be adaptable to performing wavelength broadcasting wherein each of a number of input signals can be simultaneously converted into a number of output wavelengths. The multi-channel mixer should enable broadcasting by simultaneous utilization of multiple short wavelength channels.

Still another object of the invention is to ensure that the multi-channel optical mixer and engineering methods of the invention can be employed in optical networks such as WDM, DWDM, TDM and other networks.

Yet an additional object is to provide a multi-channel optical frequency mixer having the property of polarization-insensitive operation.

These and numerous other advantages of the present invention will become apparent upon reading the detailed description.

SUMMARY

In response to the objects set forth above, the present invention provides a multi-channel optical frequency mixer for all-optical signal processing. The multi-channel mixer has a nonlinear optical material exhibiting an effective nonlinearity d_{eff}. Further, the multi-channel mixer has a quasi-phase-matching grating defining a spatial distribution of the effective nonlinearity d_{eff} in the nonlinear optical material. The spatial distribution is defined in such a manner that a Fourier transform of it to the spatial frequency domain defines at least two short wavelength channels which are quasi-phase-matched for performing optical frequency mixing.

The Fourier transform of the spatial distribution is such that it has at least two dominant Fourier components corresponding to the at least two short wavelength channels. In one embodiment, the Fourier transform of the spatial distribution has an even number of dominant Fourier components. In another embodiment, the Fourier transform of the spatial distribution has an odd number of dominant Fourier components.

The quasi-phase-matching grating, which can include an abrupt or continuous spatial variation of d_{eff}, has predetermined grating parameters selected to produce the at least two dominant Fourier components. The grating parameters which are appropriately chosen to produce the desired Fourier transform are the local grating periods, phase reversal sequences and duty cycles. In one embodiment a grating with a uniform grating period superposed by a phase reversal sequence with a 50% duty cycle is used to produce a Fourier transform with two dominant Fourier components and hence two quasi-phase-matched short wavelength channels for all-optical signal processing. In another embodiment a grating with a uniform grating period superposed by a phase reversal sequence with a 26.5% duty cycle is used to produce a Fourier transform with three equal dominant Fourier components and thus three quasi-phase-matched channels.

In a preferred embodiment, the multi-channel mixer has optical structures for in-coupling and out-coupling light into and out of the quasi-phase-matching grating. It is further preferred that the multi-channel mixer have at least one waveguide and that the quasi-phase-matching grating be distributed within that waveguide. The multi-channel mixer can be further equipped with a mode controlling structure for controlling the mode of light admitted into the waveguide.

The multi-channel mixer is fabricated in a substrate of nonlinear optical material. The nonlinear optical material is selected, among other, for its second order susceptibility $\chi^{(2)}$ enabling it to perform the frequency mixing operations. Thus,

multi-channel mixer of the invention can perform any desired nonlinear optical frequency mixing operation. These nonlinear operations include second harmonic generation (SHG), difference frequency generation (DFG), sum frequency generation (SFG) and parametric amplification. Suitable nonlinear optical materials for performing these operations include one or more components selected among lithium niobate, lithium tantalate, $MgO:LiNbO_3$, $Zn:LiNbO_3$, $MgO:LiTaO_3$, stoichiometric lithium niobate, stoichiometric lithium tantalate, potassium niobate, KTP, isomorphs of KTP such as KTA, RTA, RTP, as well as GaAs and other members of the III-V semiconductor family. Of course, other suitable nonlinear optical materials can also be used in the multi-channel mixer of the invention.

As noted above, it is preferred that the mixer have a waveguide fabricated in or on the substrate made of the nonlinear optical material. For example, the waveguide is an in-diffused waveguide produced by a suitable method, as will be known to those skilled in the art.

The multi-channel mixer of the invention can have a polarization control system for rendering it polarization diverse. The polarization control system is typically made of several components selected among elements such as polarization mode separators, polarization rotators, optical isolators, optical circulators, optical fibers, polarization maintaining fibers and polarization controllers.

In accordance with the method of invention the spatial distribution of the effective nonlinearity d_{eff} in the nonlinear optical material is defined by the quasi-phase-matching grating. The Fourier transform of the spatial distribution defines at least two short wavelength channels quasi-phase-matched for performing optical frequency mixing. At least two dominant Fourier components correspond to these at least two short wavelength channels. Specifically, grating parameters such as grating periods, phase reversal sequences and duty cycles are set to produce these at least two dominant Fourier components. Appropriate choice of phase reversal sequence or sequences is used to set the number of dominant Fourier components. The grating periods are selected to define the location of the dominant Fourier components.

The light can be in-coupled and out-coupled of the quasi-phase-matching grating using appropriate optical structures (e.g., lenses, wave guide mode filters, waveguide tapers, waveguide directional couplers etc.). Typically, the light comprises one or more beams. For the purpose of all-optical signal processing, one or more of these beams can be impressed with information.

In some embodiments the second order susceptibility of the nonlinear optical material is used twice in cascaded optical frequency mixing; $\chi^{(2)}:\chi^{(2)}$ (cascaded mixing *per se* being known to those skilled in the art). These schemes allow one to perform two frequency mixing operations in the same quasi-phase-matching grating (e.g., SHG and DFG).

It is also noted that the light in-coupled into the quasi-phase-matching grating can comprise at least two long wavelength beams. In these situations, the optical frequency mixing can be performed simultaneously on the long wavelength beams.

Thus, in general, the invention provides a method for engineering multi-channel mixers by selecting the spatial distribution of the effective nonlinearity d_{eff} of the nonlinear optical material such that at least two short wavelength channels are quasi-phase-matched for performing optical frequency mixing.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1A is a diagram illustrating the principles of quasi-phase-matched nonlinear mixing in a single channel optical frequency mixer in accordance with the prior art.

Fig. 1B is a diagram illustrating second harmonic generation (SHG) and difference frequency generation (DFG) using the single channel optical frequency mixer of Fig. 1A in accordance with the prior art.

Fig. 2 is a diagram illustrating the fundamental concepts of using the Fourier transform for engineering multi-

channel optical frequency mixers in accordance with the invention.

Fig. 3A is a diagram illustrating a two-channel mixer obtained by a superposition of a phase reversal sequence on a QPM grating with a uniform grating period.

Fig. 3B is a graph of the Fourier transform of the superposition of the phase reversal sequence and grating of the two-channel mixer of Fig. 3A.

Fig. 4 illustrates difference frequency generation (DFG) using two wavelength channels produced by the grating of Fig. 3A.

Fig. 5 is a diagram illustrating the superposition of a phase reversal sequence with a 26.5% duty cycle on a QPM grating with a uniform grating period.

Fig. 6 is an isometric view of a multi-channel frequency mixer in accordance with the invention.

Fig. 7 is a generalized multi-channel mixer in accordance with the invention.

Fig. 8A-D illustrates devices employing multi-channel mixers of the invention for WDM purposes.

Fig. 9 shows a multi-channel mixer with a polarization control system for rendering it polarization insensitive.

Fig. 10 are graphs illustrating SHG conversion efficiencies for 2-, 3- and 4-channel mixers in accordance with the invention.

DETAILED DESCRIPTION

THEORY REVIEW AND PRIOR ART DISCUSSION

The method of the invention will be best understood by first reviewing the theory of quasi-phase-matching based on prior art quasi-phase-matching grating **10** of Fig. 1A. Grating **10** is a uniform quasi-phase-matching (QPM) grating **10** of length L and is fabricated in a nonlinear optical material **12**. Material **12** has a second order nonlinear susceptibility $\chi^{(2)}$ enabling it to perform optical frequency mixing operations. The nonlinear susceptibility of material **12** is characterized by a spatial distribution of nonlinearity in material **12**. In single-domain bulk form of material **12** the distribution is described by a nonlinear coefficient d_o.

In the present case, the spatial distribution of the nonlinearity varies in a manner conveniently described with the aid of normalized nonlinearity distributions. As shown in transverse cross section or slice **16** of material **12**, the nonlinearity has a normalized nonlinearity distribution d(x,y) in the x-y plane with a value normalized to range from 0 to 1. Further, the nonlinearity has a normalized nonlinearity distribution d(z) along the z axis normalized to range from 1 to -1. (It is noted that in some cases such factorization of the nonlinearity distribution to d(x,y) and d(z) may not be possible). Here, the z-axis is conveniently chosen as the direction along which optical frequency mixing is performed (direction of light propagation).

The nonlinear coefficient d_o expressed with the aid of its normalized nonlinearity distributions is related to the second order nonlinear susceptibility $\chi^{(2)}$ by:

$$\chi^{(2)} = 2d_o d(x,y)d(z).$$

QPM grating **10** has a number of regions **14** of alternating sign of nonlinear susceptibility $\chi^{(2)}$, as indicated by the arrows. This is easily accomplished by engineering the nonlinearity such that the sign of the normalized nonlinearity distribution d(z) in adjacent regions **14** alternates between -1 and 1. Methods for engineering the nonlinearity to achieve such distribution d(z) are known in the art. For example, if material **12** is a ferroelectric it can be periodically poled. A person skilled in the art will be familiar with numerous other methods for engineering the nonlinearity depending on the type of material **12**.

Light waves of different frequencies traveling through nonlinear optical material **12** experience phase slip with respect to one another. This is because they see different indices of refraction in material **12** causing them to propagate at different phase velocities. In other words, they experience a phase velocity mismatch. Nonlinear optical frequency mixing involves a driving nonlinear polarization and interacting light waves at two or more frequencies and is thus affected by phase slip. QPM grating **10** periodically counteracts the effects of the phase slip because the second order susceptibility $\chi^{(2)}$ in adjacent regions **14** is engineered to alternate in sign. Specifically,

the thickness of regions **14** is such that when the driving polarization and interacting waves have slipped off by π, as it happens over a certain distance of travel referred to as the coherence length L_c, they enter into the next region **14** with reversed sign of linear susceptibility $\chi^{(2)}$. In other words, the thickness of regions **14** is set to the value of the coherence length L_c. Consequently, the driving polarization and interacting waves which slip off by π over coherence length L_c and would, due to their out-of-phase relationship, reverse the nonlinear frequency mixing operation over the next coherence length L_c (thus undoing the results of frequency mixing performed over the first coherence length L_c), continue to perform the desired frequency mixing operation in the subsequent region **14**. Based on this, it is also clear that QPM grating **10** should strive for a large number of regions **14** (i.e., large length L) to increase the efficiency of nonlinear mixing.

It is further useful to consider the action of QPM grating **10** during a particular nonlinear mixing process involving light of three different frequencies (three-wave mixing). This process can be a difference frequency generation (DFG) operation involving a short wavelength beam **18**, frequently referred to in such cases as a pump beam, and a long wavelength beam **20**, frequently referred to such cases as a signal beam, and an output beam **22**, which is also at a long wavelength. Short wavelength beam **18** is defined by an electric field E_p propagating at an angular frequency ω_p and having a corresponding wave vector k_p. Long wavelength beam **20** is defined by an electric field E_s at an angular frequency ω_s and a wave vector k_s. Similarly,

output beam **22** is defined by an electric field E_{out} at an angular frequency ω_{out} and a wave vector k_{out}. The phase mismatch Δk of these three beams **18, 20, 22** is counteracted by a grating vector k_g of QPM grating **10** related to regions **14** via the period Λ_g ($k_g=2\pi/\Lambda_g$) as follows:

$$k_p - k_s - k_{out} = 2\pi\left(\frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_{out}}{\lambda_{out}}\right) = \Delta k = k_g .$$

In this equation n_p, n_s, n_{out} are the respective indices of refraction experienced by beams **18, 20, 22** at their respective frequencies, here expressed in terms of their corresponding wavelengths λ_p, λ_s, λ_{out}.

When pump beam **18** and signal beam **20** enter QPM grating **10** they start to generate output beam **22** by DFG using the second order nonlinear susceptibility $\chi^{(2)}$ of material **12**, as shown in Fig. 1B. (A person skilled in the art will recognize that other nonlinear mixing processes also take place within material **12**. These are not discussed at this point for reasons of clarity.) The nonlinear mixing process is driven by the nonlinear polarization P_{NL} set up in material **12**, as illustrated in slice **16** of material **12** in Fig. 1A. Disregarding the dispersive nature of nonlinear susceptibility $\chi^{(2)}$, nonlinear polarization P_{NL} is established in proportion to the nonlinear susceptibility $\chi^{(2)}$ and also in proportion to the square of the total electric field E^2 of all three interacting waves or beams **18, 20** and **22**. This relationship can be expressed as:

$$P_{NL} = \frac{1}{2}\chi^{(2)}\varepsilon_o E_p^2,$$

where ε_o is the permittivity of free space. As these three beams **18, 20** and **22** propagate through material **12**, QPM grating **10** does not allow nonlinear polarization P_{NL} driving the frequency conversion process and the beams to slip out of phase by any more than π, as explained above. Hence, efficient generation of output beam **22** at angular frequency ω_{out} takes place over length L of QPM grating **12**.

From the above equations, it can be shown that the portion of nonlinear polarization $P_{NL,out}$ responsible for DFG generation of output beam **22** is described by:

$$P_{NL,out} = 2d_o d(x,y)d(z)\varepsilon_o E_p E_s^*,$$

where the asterisk denotes the conjugate of electric field E_s of long wavelength beam **20**. This process is visualized in Fig. 1B, where it is seen that short wavelength beam **18** at ω_p mixes with long wavelength beam **20** at ω_s to produce output beam **22** at ω_{out} "mirrored" with respect to half the pump frequency $\omega_p/2$ by DFG. Thus, output beam **22** depends on the conjugate electric field E^*_s of electric field E_s of long wavelength beam **20**.

It should be noted that the DFG conversion has a predetermined efficiency less than 100% and thus the intensity of output beam **22** is lower than that of long wavelength beam **20**. (In fact, under most conditions the output power, P_{out} is proportional to the product of pump power and signal power.) It should also be

noted that same QPM grating **10** can be used to perform second harmonic generation (SHG) of short wavelength beam **18** at ω_p by using a long wavelength beam **24** at $\omega_p/2$. In this case, long wavelength beam **24** at $\omega_p/2$ is commonly referred to as the pump. The SHG process is well-known and also indicated in Fig. 1B. The quasi-phase-matching condition for SHG is:

$$k_{\omega_p} = 2k_{\omega_p/2} - k_g .$$

QPM grating **10** has a wide tuning range or bandwidth BW_s for performing DFG using short wavelength beam **18**. For example, long wavelength beam **20** can be substituted by another long wavelength beam **20′** having an angular frequency ω'_s substantially larger than ω_s, and a wave vector k'_s correspondingly larger than wave vector k_s of beam **20**. Now, output beam **22′** is reflected about $\omega_p/2$ by DFG to a lower angular frequency ω'_{out} with a correspondingly smaller wave vector k'_{out} than output beam **22.** Thus, the DFG process using short wavelength beam **18** remains substantially quasi-phase-matched by QPM grating **10.** In other words, because the wave vectors of input and output beams **20, 22** change in opposite sense grating vector k_g still approximately satisfies the condition that:

$$k_p - k_s' - k_{out}' = k_g .$$

By virtue of this property of QPM grating **10,** tuning bandwidth BW_s for long wavelength beam **20** when performing DFG with a fixed short frequency beam **18** is typically on the order of tens of nanometers in wavelength.

Unfortunately, the same is not true for a tuning range or bandwidth BW_p for short wavelength beam **18.** In general, short wavelength beam **18** can only be tuned over a very narrow bandwidth (typically only a few nm or less) while still maintaining the quasi-phase-matching condition in QPM grating **10.** In other words, only one narrow short wavelength channel defined by bandwidth BW_p is available for short wavelength beam **18.** In this sense QPM grating **10** employed in nonlinear material **12** can only yield a single short wavelength channel optical frequency mixer. Such single channel mixer has only limited usefulness for optical signal processing, e.g., all-optical processing, as already remarked in the background section.

EMBODIMENTS OF THE INVENTION

In accordance with the invention, a multi-channel optical frequency mixer **50**, as shown in Fig. 2, is made in a nonlinear optical material **52.** Material **52** is selected for its second order nonlinear susceptibility $\chi^{(2)}$ as well as other material properties known to a person skilled in the art to be used for the desired optical frequency mixing operation or operations. Materials which can be used in optical material **52** can be selected from among lithium niobate, lithium tantalate, $MgO:LiNbO_3$, $Zn:LiNbO_3$, $MgO:LiTaO_3$, stoichiometric lithium niobate, stoichiometric lithium tantalate, potassium niobate, KTP, isomorphs of KTP such as KTA, RTA, RTP, as well as GaAs and other members of the III-V semiconductor family. A person skilled in the art will realize that numerous other materials and groups of materials exhibiting suitably large nonlinear

susceptibility $\chi^{(2)}$ and other advantageous material properties for optical frequency mixing are available and can be used in optical material **52.**

A quasi-phase-matching grating **54** defines a spatial distribution of an effective nonlinearity d_{eff}. QPM grating **54** is engineered to yield a particular Fourier transform of the effective nonlinearity d_{eff}. Specifically, the spatial distribution of the effective nonlinearity d_{eff} is defined by QPM grating **54** in such manner that the Fourier transform of that spatial distribution to the spatial frequency domain defines at least two short wavelength channels **56, 58** which are quasi-phase-matched for performing optical frequency mixing.

Grating **54** has a number of regions **64** in which the normalized nonlinearity distribution d(z) has a different magnitude or sign. For example, the normalized nonlinearity distribution d(z) in adjacent regions **64** exhibits a sign reversal. Regions **64** do not form a grating with a single uniform grating period Λ_g. In fact, grating **54** is made up of several components. In the embodiment shown, grating **54** has a grating period Λ_g with a 50% duty cycle superposed by a first phase reversal sequence Π_1 of period Λ_{phase1} with a 50% duty cycle and by a second phase reversal sequence Π_2 of period Λ_{phase2} also with a 50% duty cycle.

Conveniently, the superposition of grating period Λ_g by phase reversal sequences with periods Λ_{phase1} and Λ_{phase2} can be defined in terms of an effective nonlinearity d_{eff} along the z-direction as:

$$d_{eff}(z) \equiv d_o d(x,y) G_m ,$$

where G_m is a Fourier coefficient of the Fourier decomposition of $d_{eff}(z)$ and d_o is the effective nonlinear coefficient of bulk material **52**. It is known in the art of mathematics that periodic functions can be Fourier decomposed into a Fourier series. It is also known that Fourier series can be appropriately chosen to produce certain desired functions. The components of the Fourier series exist in an adjoint space. In the case of the spatial distribution of d_{eff} defined by grating **54**, the adjoint space is the spatial frequency domain. The Fourier transform of the effective nonlinearity d_{eff} defined by grating **54** thus defines Fourier components in the spatial frequency domain.

In free space spatial frequencies associated with light waves are conveniently characterized by wave vectors k. Inside nonlinear material **52**, however, wave vectors k are replaced by propagation constants β, which vary with angular frequency ω of the wave, i.e., $\beta=\beta(\omega)$. That is because within nonlinear material **52** propagation constant β experiences dispersion. The group velocity v_g of any light wave of bandwidth $\Delta\omega$ in medium **52** can be expressed as:

$$v_g = \left(\frac{d\beta}{d\omega}\right)_{\omega_c} ,$$

evaluated at central frequency ω_c of bandwidth $\Delta\omega$. This linear relationship does not take into account higher order dispersion

terms and hence can only be used to the extent that higher order terms in the relationship between ω and β can be neglected. In some nonlinear frequency mixing processes, e.g., in interactions between two light beams whose wave vectors k are near-degenerate or degenerate, the above linear relationship will not be sufficient to establish the relationship between ω and β. That is because the linear terms will cancel and hence the higher order terms will become important. In these cases a Taylor expansion around the center angular frequency ω_c can be performed to obtain the higher order terms and thus obtain a sufficiently accurate relationship between β and ω.

In cases where β and ω are related by the linear relationship, the Fourier components existing in the spatial frequency domain are related to the temporal frequency domain, i.e., they are related to angular frequencies ω via the reciprocal of group velocity, $1/v_g$, and in the case of a bandwidth $\Delta\omega$ they are related via $1/\Delta v_g$. A person skilled in the art of mathematics will be able to derive the appropriate relationship between ω and β for cases where higher order terms are important. Thus, the Fourier transform corresponds to components **56, 58, 60** and **62** in the time frequency domain, as will also be appreciated by a person skilled in the art of mathematics. In fact, components **56, 58, 60** and **62** are the four major or dominant Fourier components corresponding to angular frequencies ω_{p1}, ω_{p2}, ω_{p3} and ω_{p4}, as shown in Fig. 2. In other words, the tuning curve defining the relative conversion efficiency η_{rel} versus angular frequency ω of pump beams in QPM grating **54** has four main peaks at **56, 58, 60** and **62**.

Multi-channel mixer **50** is thus a four-channel device and is capable of performing optical mixing operations with short wavelength beams contained in the four short wavelength channels centered at angular frequencies ω_{p1}, ω_{p2}, ω_{p3} and ω_{p4}. In other words, grating **54** ensures that the quasi-phase-matching condition is satisfied for optical frequency mixing operations which use short wavelength beams at these four frequencies.

Figs. 3A and 3B show in more detail the engineering of a two-channel optical mixer **75** using a QPM grating **70** in accordance with the invention. Referring to Fig. 3A, it is shown that QPM grating **70** is obtained by superposing a phase reversal sequence **72** of period Λ_{phase} with a substantially 50% duty cycle on a uniform QPM grating **74** of period Λ_g and a substantially 50% duty cycle. By itself, uniform QPM grating **74** yields a single channel device. That is because the Fourier transform of a uniform grating or, equivalently, of a periodic square function, is a sinc function with a single dominant Fourier component **76** corresponding to ω_p as indicated in Fig. 3B. Because grating **70** also contains phase reversal sequence **72**, the Fourier transform of QPM grating **70** is the convolution of the sinc function representing the Fourier transform of grating **74** and a comb function, in this case with two major peaks and a number of minor peaks due to phase reversal sequence **72**. This convolution produces two dominant Fourier components **78, 80** corresponding to angular frequencies ω_{p1} and ω_{p2}. It should be noted that to first order these two angular frequencies are evenly spaced from the angular frequency ω_p of single-channel grating **74**. Thus,

adding phase reversal sequence **72** has caused a split of the dominant Fourier component **76** of uniform grating **74** into dominant Fourier components **78, 80.**

The Fourier transform of QPM grating **70** also has a number of peaks or higher order harmonics, generally indicated by **82.** The harmonics are due to the "squareness" of grating **74.** These higher order harmonics **82** are small in comparison to dominant Fourier components **78, 80** and will generally not be relied upon for performing optical frequency mixing. It will be understood by a person skilled in the art that such higher order harmonics may be generally eliminated by use of filter design techniques including, but not limited to apodization of QPM grating **70.** Meanwhile, dominant Fourier components **78, 80** correspond to the two channels centered at frequencies ω_{p1} and ω_{p2} of two-channel QPM grating **70.**

The operation of two-channel mixer **75** based on an exemplary DFG process is illustrated in Fig. 4. As in Fig. 1B, light beams are represented by arrows indicating beam intensities centered at corresponding center angular frequencies. In contrast to prior art devices, two-channel mixer **75** accepts two short wavelength beams **90, 92** at angular frequencies ω_{p1} and ω_{p2} corresponding to dominant Fourier components **78, 80.** Since the operation being performed is DFG short wavelength beams **90, 92** are acting as pump beams in this case. Each beam **90, 92** has a tuning bandwidth BW_{p1}, BW_{p2} which is related to the associated dominant Fourier component as the width of the spatial Fourier transform scaled by Δv^{-1}. When a long wavelength beam **94,** in

this case a signal beam, at angular frequency ω_s is input into two-channel mixer **75** it produces a first output beam **96** at angular frequency ω_{out1} by DFG with beam **90** via nonlinear susceptibility $\chi^{(2)}$. Beam **94** can also produce a second output beam **98** at angular frequency ω_{out2} by DFG with beam **92.** (It should be noted that beams **90** and **92** do not need to be present in mixer **75** simultaneously.) Hence, QPM grating **70** engineered according to the invention defines two short wavelength channels, centered at ω_{p1} and ω_{p2}, quasi-phase-matched for performing optical frequency mixing, in this case DFG.

Beams **90, 92** can be input into mixer **75** simultaneously or at different times to perform DFG with long wavelength beam **94** simultaneously or at different times. Also, more than one long wavelength beam can take advantage of the two pump beams for optical frequency mixing operations. For example, two or more long wavelength beams can be supplied to mixer **75** and the optical frequency mixing can be performed simultaneously on these two or more long wavelength beams. Of course, two-channel mixer **75** can also be used to perform other optical frequency mixing operations. These nonlinear operations can involve second harmonic generation (SHG), sum frequency generation (SFG) and parametric amplification. It is also possible to perform several different mixing operations in mixer **75** at the same time, e.g., SHG and DFG, as will be appreciated by those skilled in the art. For example, this can be done by using the second order susceptibility of the nonlinear optical material twice in cascaded optical frequency mixing; $\chi^{(2)}:\chi^{(2)}$. Cascaded schemes are known in the art and allow one to perform two frequency

mixing operations in the same quasi-phase-matching grating (e.g., SHG and DFG).

Two-channel mixer **75** with QPM grating **70** has taken advantage of the Fourier transform of phase reversal sequence **72** to "split" the one short wavelength channel offered by QPM grating **74** into two short wavelength channels. Referring back to QPM grating **54**, the superposition of two phase reversal sequences on a uniform grating "splits" one short wavelength channel offered by the uniform grating into four short wavelength channels. In fact, a person skilled in the art of mathematics will recognize that any desired even number of dominant Fourier components and hence even number of short wavelength channels can be produced by a superposition of the appropriate number of phase reversal sequences on a uniform grating. Of course, a person skilled in the art will also be familiar with the nature of the Fourier transform and appreciate that there are many ways in which the spatial distribution of the effective nonlinearity d_{eff} can be engineered to produce an even number of dominant Fourier components and hence short wavelength channels.

In some embodiments an odd number of short wavelength channels is required in multi-channel mixer **75**. Fig. 5 illustrates uniform grating **74** superposed by a phase reversal sequence **73** with a duty cycle of approximately 26.5%. The Fourier transform of the spatial distribution of a QPM grating produced by this superposition has three equal amplitude dominant Fourier components. Specifically, in addition to the two new dominant Fourier components corresponding to ω_{p1} and ω_{p2}, it retains a

dominant Fourier component corresponding to the location of the original dominant Fourier component of uniform grating **74**, i.e., at ω_p. A person skilled in the art of mathematics will recognize that by altering the duty cycles of phase reversal sequences it is possible to engineer QPM gratings with an odd number of dominant Fourier components.

In some embodiments grating **74** can additionally contain a chirp. The chirp can be produced in grating **74** to compress the light by counteracting phase dispersion during the frequency mixing process. Techniques for chirping QPM gratings are known in the art and a skilled artisan will find information on its implementation, e.g., in U.S. Pat. No. 5,815,307 to M. Arbore et al.

The QPM grating engineering techniques of the invention can be used to make a variety of multi-channel mixers in various configurations. Fig. 6 is an isometric view of a multi-channel mixer **100** equipped with a QPM grating **102** provided in a substrate **104**. Conveniently, entire substrate **104** is made of a nonlinear optical material **101** or materials which are to perform optical mixing operations expected of multi-channel mixer **100**. Thus, nonlinear optical material **101** can consist of one or more of material components including without limitation, lithium tantalate, $MgO:LiNbO_3$, $Zn:LiNbO_3$, $MgO:LiTaO_3$, stoichiometric lithium niobate, stoichiometric lithium tantalate, potassium niobate, KTP, isomorphs of KTP such as KTA, RTA, RTP, or GaAs or other members of the III-V semiconductor family as well as any organic nonlinear materials and nonlinear polymers. A person

skilled in the art will recognize that the exact choice of material depends on various considerations including the type of mixing operations which will be performed in QPM grating **102.** In fact, even organic nonlinear materials and nonlinear polymers could be used as material **101.**

QPM grating **102** is made up of domains or regions **106** defining a spatial distribution of the effective nonlinearity d_{eff}. To achieve this, regions **106** can be formed by appropriate growth of regions **106** to produce different non-linear orientations in adjacent regions **106.** Alternatively, regions **106** can be obtained by poling in cases when material **101** is a ferroelectric material, a polymer or glass. A person skilled in the art will appreciate that there are numerous techniques which can be used to produce regions **106** as required for grating **102** depending on the type of material **101** selected.

QPM grating **102** is distributed within a waveguide **110.** The use of waveguide **110** in material **101** is preferred because it aids in guiding the interacting light beams and generally results in better conversion efficiencies during the nonlinear optical mixing operations as compared to bulk material. For example, waveguide **110** is fabricated within nonlinear optical material **101** after QPM grating **102.** When nonlinear optical material **101** is $LiNbO_3$ or $LiTaO_3$ waveguide **110** may comprise waveguide structures that include, without limitation, annealed proton exchanged (APE) waveguides, buried waveguides, metal in-diffused waveguides (including metals such as zinc, titanium, etc.) as will be understood by those knowledgeable in the art.

Waveguide **110** has an input facet **112** and an output facet **114.** In the present embodiment, input facet **112** and output facet **114** are located at opposing side walls of substrate **104.** Input facet **112** has an associated in-coupling or coupling element **116,** in this case a lens, for in-coupling light **118** into waveguide **110.** An out-coupling element **120** is provided past output facet **114** for guiding output light **122** exiting through output facet **114.** A person skilled in the art will recognize that other coupling devices such as tapers in waveguide **110** can be employed in conjunction with or without a lens to serve the function of coupling elements **116** and **120.** In general, coupling element **116** and coupling element **120** may include without limitation optical elements such as optical fiber, prism couplers, waveguide mode filters, waveguide couplers, and tapered waveguide regions. In particular, mode controlling structures for controlling the mode of light admitted into waveguide **110** can be used to maximize the overlap of interacting beams. As is known in the art, maximizing this overlap will ensure high efficiency of the frequency mixing operations performed by multi-channel mixer **100.** A person skilled in the art will appreciate that the best choice of coupling element **116** is made by considering the wavelengths and modes of light which are to be coupled into QPM grating **102.**

In the present embodiment, substrate **104** also has a waveguide **124** with an input facet **126** and an associated in-coupling element **128** for in-coupling additional light **130.** This arrangement can be used when light **130** is not required for the

nonlinear mixing operation in first section of QPM grating **102** or if it can not be efficiently in-coupled together with light **118** via in-coupling element **116.** Once again, coupling element **128** can include an appropriate taper of the waveguide **124** and/or any of the optical elements listed above.

Waveguide **124** is formed such that it extends next to and parallel to waveguide **110** where QPM grating **102** is distributed. This arrangement forms a coupling or junction **132** between waveguides **124** and **110** and permits light **130** to be in-coupled via the evanescent field into waveguide **110.** A person skilled in the art will recognize that junction **132** is merely one exemplary structure for accomplishing this goal and that light **130** can be in-coupled into waveguide **110** using other types of junctions which may include without limitation, Y-junctions and directional couplers.

QPM grating **102** is multi-channel. Specifically, QPM grating **102** is two-channel for quasi-phase-matching optical frequency mixing operations which use two short wavelength channels ω_{p1} and ω_{p2}. Thus, QPM grating **102** is analogous to QPM grating **70** discussed above.

During operation, in-coupling element **116** couples light **118** into waveguide **110** and QPM grating **102.** In the present embodiment light **118** contains two long wavelength beams at angular frequencies ω_1, ω_2. Angular frequencies ω_1, ω_2 are chosen to be half the frequencies of short wavelength channels ω_{p1} and ω_{p2} respectively. For illustrative purposes Fig. 6 shows only

portions of these beams in the form of pulses. It will be understood, however, that continuous-wave beams can be used for any of these beams.

The first section of QPM grating **102** is used to generate two second harmonics at ω_{p1} and at ω_{p2} of long wavelength beams at ω_1, ω_2. It should be noted long wavelength beams at ω_1, ω_2 play the role of pump beams within the first section of QPM grating **102** when generating the second harmonics at ω_{p1} and at ω_{p2}. The two second harmonics, which are short wavelength beams, continue to propagate into the second section of QPM grating **102.**

Light **130** in the form of two additional long wavelength beams at ω_3 and ω_4 couples into waveguide **110** at junction **132.** These two beams propagate into second section of QPM grating **102** along with second harmonics at ω_{p1} and ω_{p2}. In second section of QPM grating **102** second harmonics ω_{s1} and ω_{s2} obtained in the first section of QPM grating **102** act as pump beams. Specifically, in the second section they mix with long wavelength beams at ω_3, ω_4 to produce output light **122** by DFG. DFG between ω_{p1}, and ω_3, ω_4 respectively generates output beams ω_{out1}, ω_{out2} while DFG between ω_{p2}, and ω_3, ω_4 respectively generates output beams ω_{out3}, ω_{out4}. Output light **122** is out-coupled from multi-channel mixer **100** via coupling element **120.**

The power conversion performance of QPM grating **102** in the small signal limit the output power can be expressed as:

$$P_{\omega_{out}} \approx \eta_{norm} P_{\omega_S} P_{\omega_P} \left| \frac{1}{L} \int_0^L \Pi(z) \exp(-j\Delta\beta z) dz \right|^2 \qquad \text{eq. 1}$$

where $P_{\omega P}$, $P_{\omega S}$ and $P_{\omega out}$ are conventionally referred to as pump, signal and converted output powers expressed in terms of their angular frequencies. For example, in the first section of QPM grating **102** during SHG generation of ω_{P1} $\omega_P=\omega_1$ and $\omega_S=\omega_1$, and $P_{\omega out}$ is the power of second harmonic generated at ω_{P1}. For DFG generation of ω_{out1} in the second section of QPM grating **102** $\omega_P=\omega_{P1}$ and $\omega_S=\omega_3$, and $P_{\omega out}$ is the power of the DFG output beam at ω_{out1}. η_{norm} is the normalized efficiency in units of W^{-1}, which is proportional to the square of the device length L (in this case the length of the first section of QPM grating **102** for SHG and the length of second section of QPM grating **102** for DFG) and the square of the modal overlap of the interacting beams with the second-order optical nonlinearity $\chi^{(2)}$ of material **101**. The term $\Delta\beta$ can be expressed as:

$$\Delta\beta = 2\pi\left(n_p/\lambda_p - n_s/\lambda_s - n_{out}/\lambda_{out} - 1/\Lambda_g\right), \qquad \text{eq. 2}$$

where the refractive indices n are the effective indices at the corresponding wavelengths λ, and $\Delta\beta$ represents the phase mismatch between the interacting waves and uniform QPM grating **74** with superposed phase-reversal sequence **72** (period Λ_{phase}). From this equation it is clear how mismatch arises due different effective indices of refraction n_p, n_s and n_{out} experienced in material **101** by pump, signal and converted output frequencies, here expressed in terms of their wavelengths λ_p, λ_s

and λ_{out}. Finally, $\Pi(z)$ is the superimposed phase-reversal sequence **72**.

In the particular case of QPM grating **102** phase-reversal sequence **72** has a grating period of Λ_{phase} and a duty cycle of 50%. Thus, first phase-reversal sequence **72** can be expressed as:

$$\Pi(z) = \sum_{n=1}^{\infty}\left(\frac{2}{\pi n}\right)\left[\exp(jK_n z) + \exp(-jK_n z)\right] \text{ where } K_n = \frac{2\pi n}{\Lambda_{phase}}. \qquad \text{eq. 3}$$

Substituting the above expression for $\Pi(z)$ into eq. 1 yields:

$$P_{\omega_{out}} \approx \eta_{norm} P_{\omega_P} P_{\omega_S} \sum_{n=1,3,5\ldots}^{\infty}\left(\frac{2}{\pi n}\right)^2\left[\operatorname{sinc}^2\left(\frac{\Delta\beta + K_n}{2}L\right) + \operatorname{sinc}^2\left(\frac{\Delta\beta - K_n}{2}L\right)\right]. \qquad \text{eq. 4}$$

For n=1 this equation results in a tuning curve with phasematching frequencies corresponding to the two dominant Fourier components (see Fig. 3B), as discussed above.

It will be clear to a person skilled in the art that the embodiment in Fig. 6 illustrates only one exemplary multi-channel optical mixer **100** which performs SHG and DFG using two short wavelength channels. The generalized embodiment in Fig. 7 illustrates a multi-channel mixer **150** which can perform a number of nonlinear mixing operations in series on various beams. Mixer **150** has a number of QPM gratings **152A, 152B, ..., 152N** engineered according to the invention. It should be noted that although gratings **152A, 152B, ..., 152N** are shown in the form of discrete gratings, they can be substituted by non-discrete

gratings. In other words, gratings **152A**, **152B**, ..., **152N** can exhibit a continuous variation in d_{eff} (e.g., $d_{eff}(z)$ varies continuously between -1 and 1). Input and output beams can be added and retrieved beetween gratings **152A**, **152B**, ..., **152N** as required with appropriate elements known in the art, e.g., directional couplers.

Mixer **150** accepts a number of input beams at frequencies ω_{in}^{1} through ω_{in}^{x}. For purposes of all-optical signal processing any one of these signals can be impressed with information. In fact, any beam can carry information irrespective of whether it is an input beam at a short wavelength corresponding to the short wavelength channel of the particular QPM grating or is a long wavelength beam. Thus, in any frequency mixing operation the beam carrying the information can be the pump beam or the signal beam or both. Methods for modulating information on optical beams are well-known in the art.

Figs. 8A-D show several example applications of multi-channel mixers according to the invention. These types of multi-channel mixers can be used in WDM, DWDM and TDM optical networks or other types of optical networks.

In Fig. 8A a multi-channel mixer **200** is used to dynamically reconfigure N converted output frequencies. In this case light in the form of long wavelength beams at N signal frequencies ω_{s1} through ω_{sN} impressed with information is input into multi-channel mixer **200**. Then, a light beam at an appropriate pump frequency ω_p is selected for performing DFG. Specifically, pump

frequency ω_p can be selected in any one of the multiple short wavelength channels for which multi-channel mixer **200** has been designed in accordance with the invention. The pump frequency ω_p determines, through DFG, the frequency of output beams at output frequencies ω_{out1} through ω_{outN} (based on $\omega_{out}=\omega_p-\omega_s$). Thus, information input at signal frequencies ω_{s1} through ω_{sN} exits multi-channel mixer **200** at output frequencies ω_{out1} through ω_{outN}. The N converted output frequencies ω_{out1} through ω_{outN} can correspond, e.g., to WDM channels of an optical network.

Fig. 8B shows a multi-channel mixer **202** used for frequency broadcasting also referred to as wavelength broadcasting. In this case light at each of N signal frequencies ω_{s1} through ω_{sN} is converted into M output frequencies by using M pump frequencies ω_{p1} through ω_{pM}. Once again, the conversion is accomplished by DFG.

Fig. 8C shows a multi-channel mixer **204** used for reconfigurably dropping frequencies or wavelengths. This is performed on N signal frequencies ω_{s1} through ω_{sN} by converting them using L pump frequencies ω_{p1} through ω_{pL} to output frequencies outside the range of frequencies supported by the WDM network. By doing this, selected signal frequencies can be dropped from the WDM network. Once again, this operation can be performed by DFG.

Fig. 8D shows a multi-channel mixer **206** used for switching or guiding N signal frequencies ω_{s1} through ω_{sN} with the aid of a reconfigurable pump frequency ω_p. It will be clear to a person skilled in the art that channel drop, switch, sample as well as

many other useful functions can be realized using multi-channel mixers **200, 202, 204** and **206** in WDM networks. In fact, multi-channel mixers **200, 202, 204** and **206** can be configured for phasematching wavelengths whose location and spacing is defined by the International Telecommunication Union (ITU) standards. Furthermore, multi-channel mixers of the invention employed in networks can use any suitable frequency mixing operation to perform the required functions. A person skilled in the art will realize that the functions of the various light beams will be chosen by the designer. Depending on the frequency mixing operation, pump beams, signal beams, low-power beams, high-power beams, continuous-wave beams, pulsed beams as they are known in the art, can all be appropriately manipulated by multi-channel mixers according to the invention and any of these beams (with the exception of continuous-wave beams) be impressed with information.

Fig. 9 shows a multi-channel mixer **210** with a polarization control system **212** for rendering mixer **210** polarization insensitive or polarization diverse. Mixer **210** has a QPM grating **214** engineered in accordance with the invention in a waveguide **215** produced in a nonlinear optical material substrate **216.** Polarization control system **212** has a polarizing beam splitter **218** for splitting light **220** delivered from a fiber **222** into its two orthogonal polarizations. After the split, p-polarized light **220A** is coupled into mixer **210** with the aid of coupling element **224** from the left. Meanwhile, s-polarized light **220B** follows a path defined by mirrors **226A, 226B** and **226C.** Along this path a coupling element **228** ensures that s-

polarized light **220B** is efficiently in-coupled into mixer **210** and a half-wave plate **230** rotates s-polarized light **220B** by 90° to coincide in its polarization state with p-polarized light **220A.** After being rotated, light **220B** is in-coupled into mixer **210** from the right.

Output light **238** from multi-channel mixer **210** exits to the right and left from mixer **210.** After retracing the paths of input light **220A** and **220B** output light **238** passes through beam splitter **218** and back into fiber **222.** The present embodiment conveniently uses a circulator **236** for managing intput light **220** and output light **238.** Light **220** is delivered from fiber **234** via circulator **236** into fiber **222.** Output light **238,** traveling in the opposite direction from light **220,** enters circulator **236** and is passed on to fiber **232.**

A person skilled in the art will recognize that polarization control system **212** can be replaced by alternative systems performing the same function. These systems can employ several components selected among elements such as polarization mode separators, polarization rotators, optical isolators, optical circulators, optical fibers, polarization maintaining fibers and polarization controllers to achieve the same functionality as system **212.**

Finally, the performance of multi-channel mixers engineered in accordance with the invention is illustrated in the graphs of Fig. 10. These graphs represent a comparison of SHG wavelength tuning curves for a single channel prior art mixer in (a), and

two-channel, three-channel and four-channel mixers in (b), (c) and (d) respectively. The closed circles are measured results and the solid lines are the theoretical fits. The efficiencies are relative to the peak efficiency ($\approx$500%/W) of a one-channel mixer.

A person skilled in the art will recognize that multi-channel mixers of the invention can be further modified in many ways to suit the particular needs at hand. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.